Status of the PHENIX Experiment at RHIC

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Some history

Strong interaction is the least understood

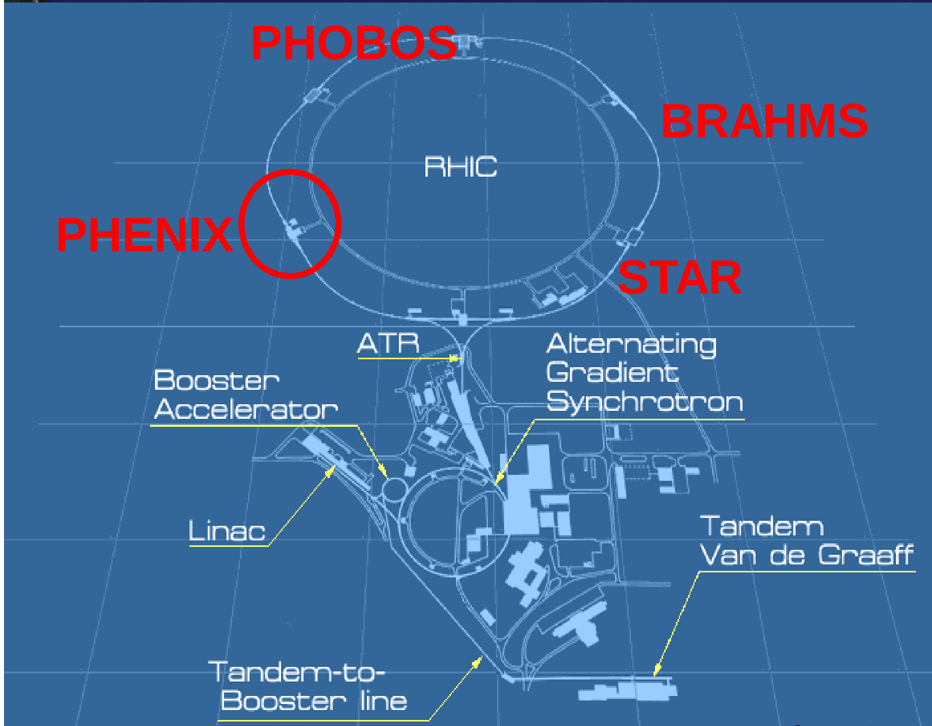
- pQCD only at high momentum transfer
- At low energy we rely on effective models or lattice
- Expected new state of matter where quarks break free (The **Quark Gluon Plasma**)

- Matsui-Satz (1986): charmonium will not bind because of Debye screening
  → Signature of QGP is J/ψ suppression
- SPS claim of finding this matter (2000)
- Problems (1) there can be concurrent effects, and
  (2) mechanisms that actually enhance #J/ψ

A dedicated collider to find QGP, find out its properties and better understand QCD: **RHIC**

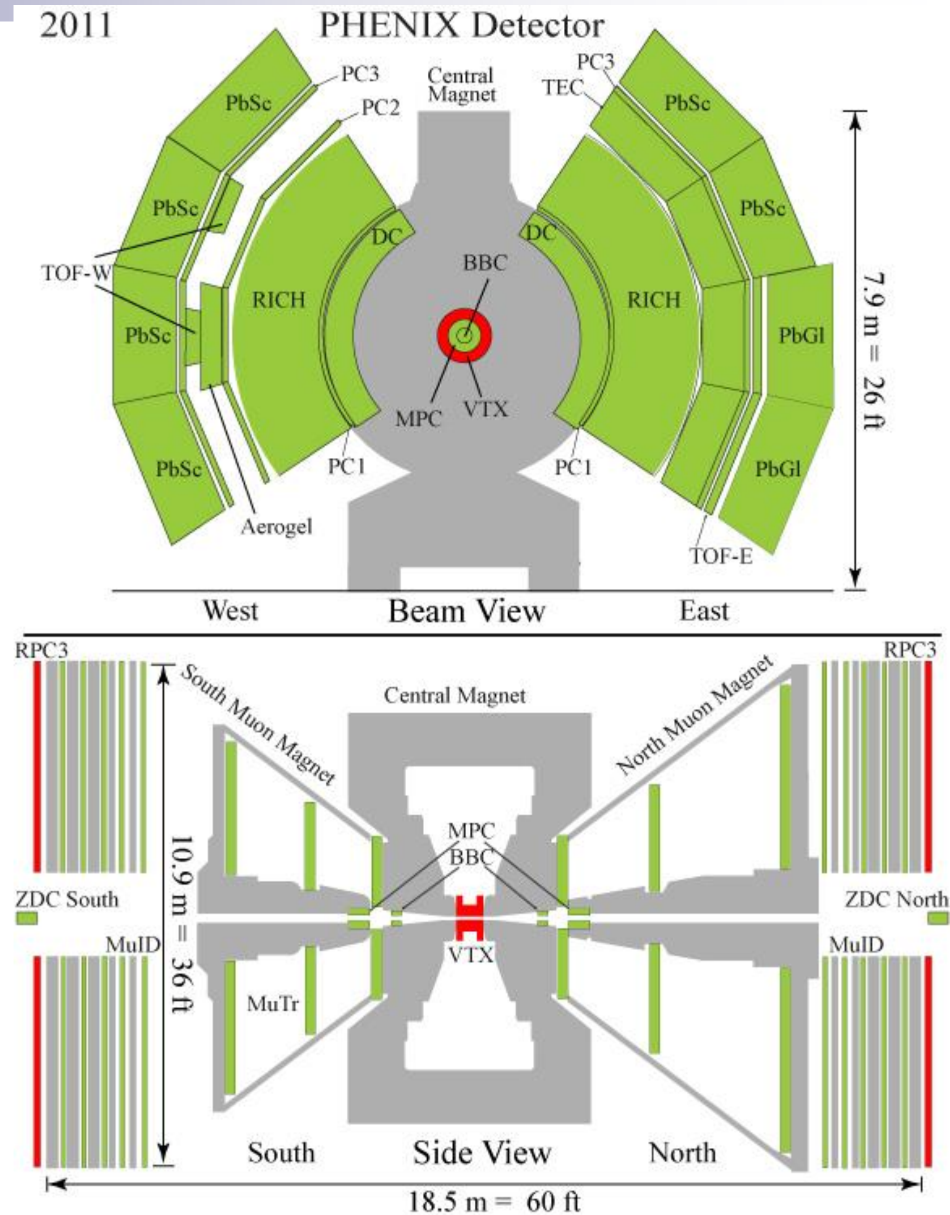
The RHIC facility

- Two independent rings
  - 3,9 km long each
- Collides heavy ions...
  - **Au+Au**, **Cu+Cu**, ...
  - $\sqrt{s_{NN}}$= 7,7 – 200 GeV
- ...and protons
  - **p+p** up to $\sqrt{s}$ = 500 GeV
  - Different polarization patterns
- Asymmetric setups
  - **d+Au**
- 4 experiments
  - All different capabilities
  - PHENIX, STAR (the „large” ones)
  - PHOBOS, BRAHMS (completed)



The PHENIX experiment

- Tracking system
  - Gas chambers at mid-rapidity
  - Dipole magnet
  - Measuring spectra and correlation of charged hadrons ($\pi^{\pm}$, $K^{\pm}$, p,)
- Calorimetry
  - π^0 , η
  - direct photons
- Identifying leptons
  - e^+e^- pairs, $\mu^{\pm}$ (forward region)
  - heavy quarkonia (J/ψ)

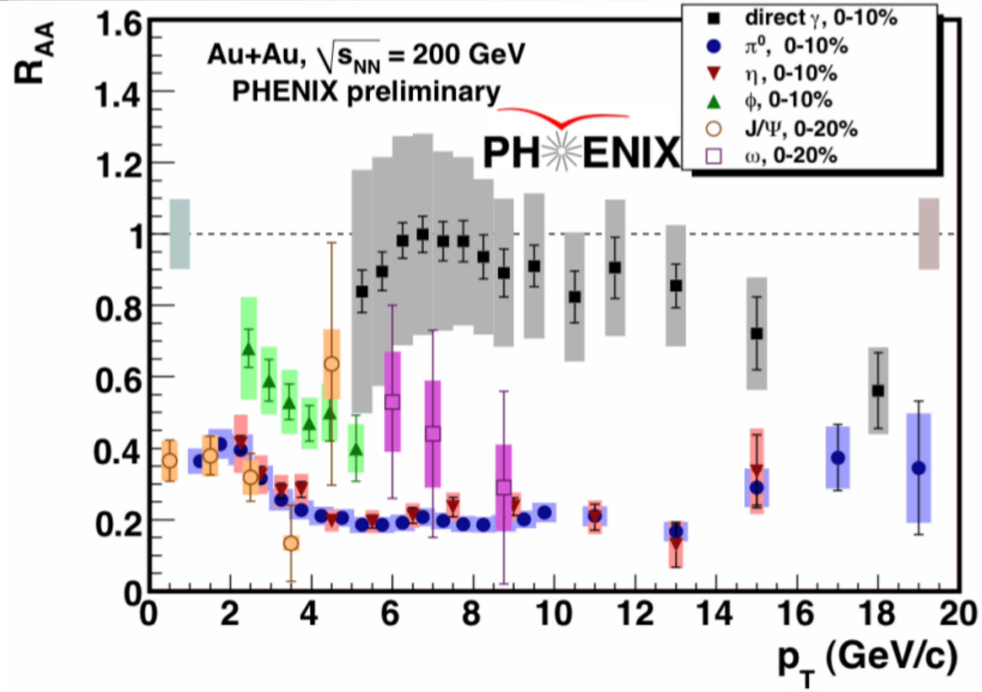


A new state of matter

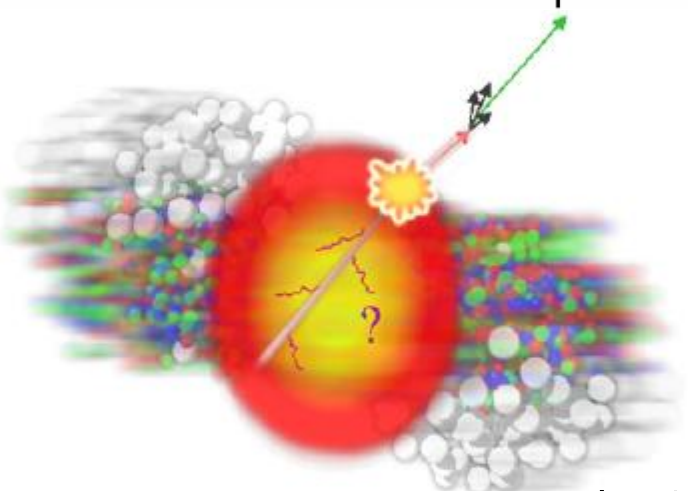
- Jet suppression
  - Central Au+Au collisions: Less high-pT hadrons than estimated from p+p

$$R_{AA} = \frac{\text{Yield}_{AA}}{\langle N_{binary} \rangle_{AA} \text{Yield}_{pp}}$$

  - Factor of 5!



- But is it really a new state of matter?
  - Direct photons are not suppressed
  - No suppression in peripheral Au+Au
  - No suppression in d+Au
  - → Final state effect → **YES!**

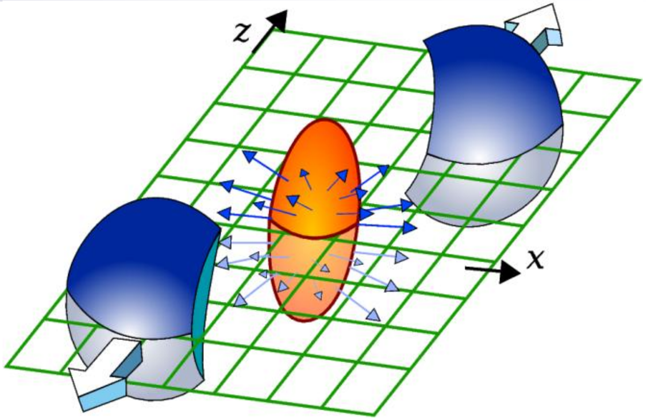


It's a perfect fluid

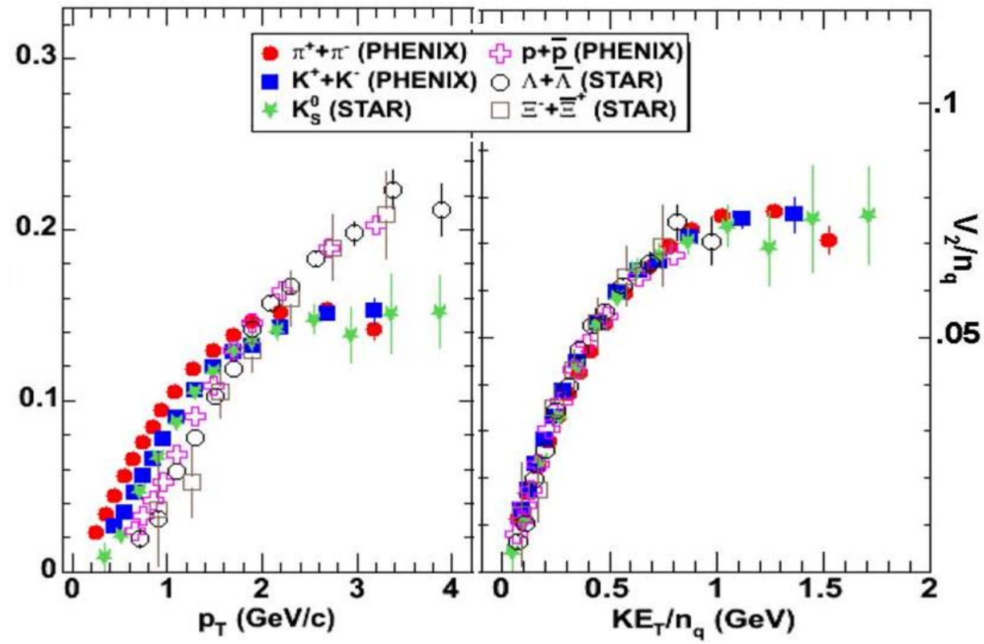
- It flows!
  - Azimuthal anisotropy w.r.t. reaction plane

$$f(\varphi) \propto \left(1 + 2\sum_{n=1}^{+\infty} v_n \cos\left[n\left(\varphi - \psi_n\right)\right]\right)$$

  - Elliptic flow v2 > 0
  - Contradicts expectations
  - Consistent with hydro models
  - Even photons flow



- It's a fluid of quarks
  - Scaling by quark number

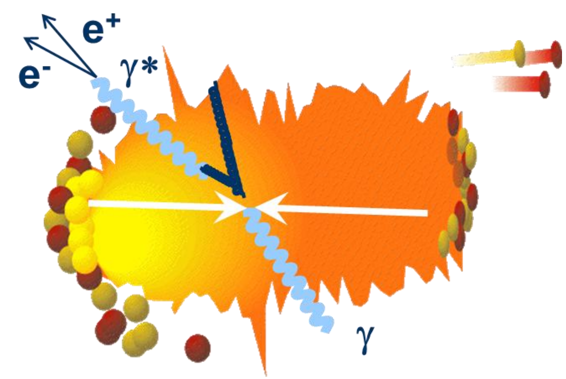


- It's the most perfect fluid
  - Viscosity near conjectured theoretical limit

$\eta/s \sim \hbar/4\pi$, $c_s = 0.35c$

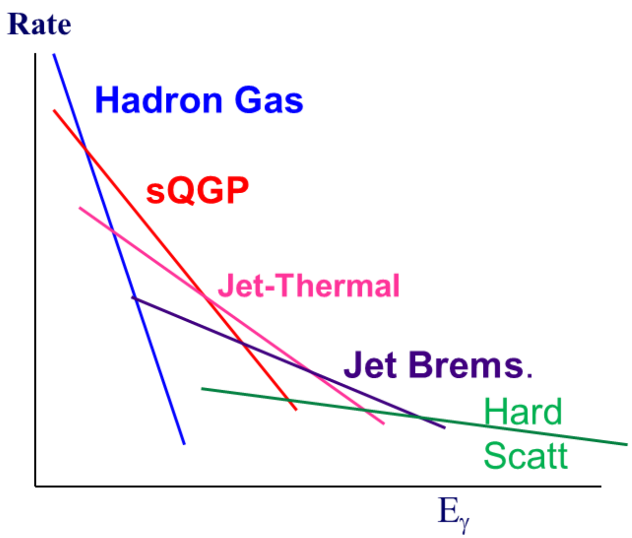
It's hot. But how hot?

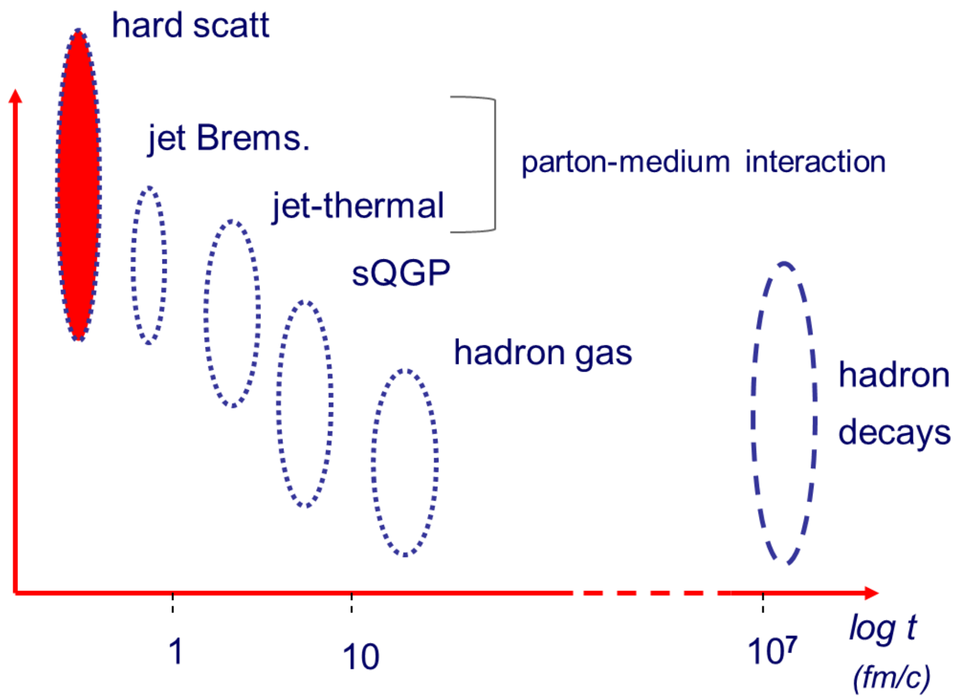
- Thermalized source of particles
  - Boltzmann-like distribution: $N(m_T) \sim e^{-mT/T}$
  - For **all hadrons**, $\mathrm{T} \sim 170\ \mathrm{MeV}$ after radial flow correction
    This is near Hagedorn's limit
  - Of course: we only see the freezeout.
    Quark matter is opaque for hadrons.
  - We need a penetrating probe



- Direct photons
  - Come from all stages of reaction
  - Extremely useful, but…
  - Extremely hard to disentangle different photon sources

Sources of photons

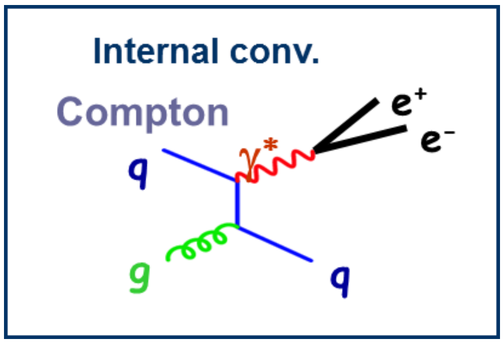


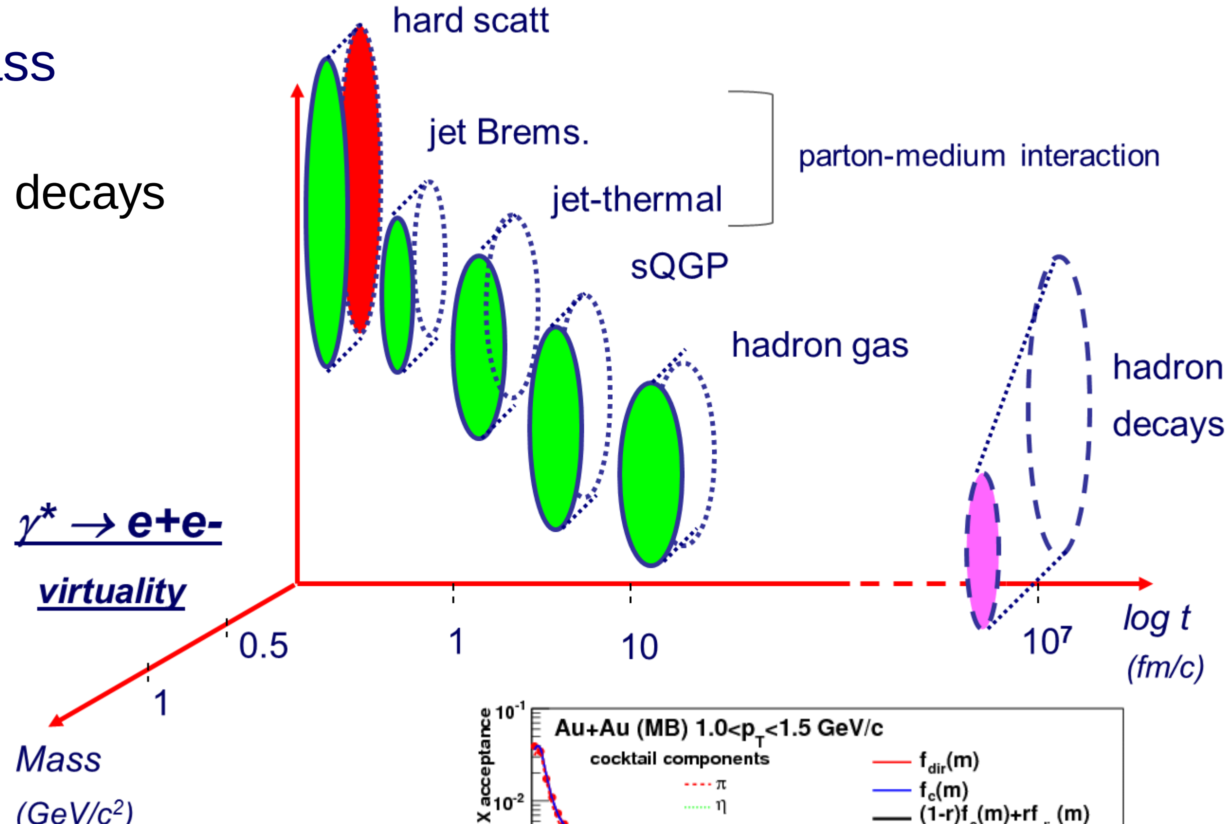


- Inclusive photon spectrum has huge background
  - Mainly $\pi^0 \rightarrow \gamma\gamma$, also other hadrons
- Precise direct photon measurement limited to p_T>2-4 GeV
  - We miss the thermal region

Sources of virtual photons

- Virtual photons have mass
  - By selecting masses, phase space of hadron decays restricted

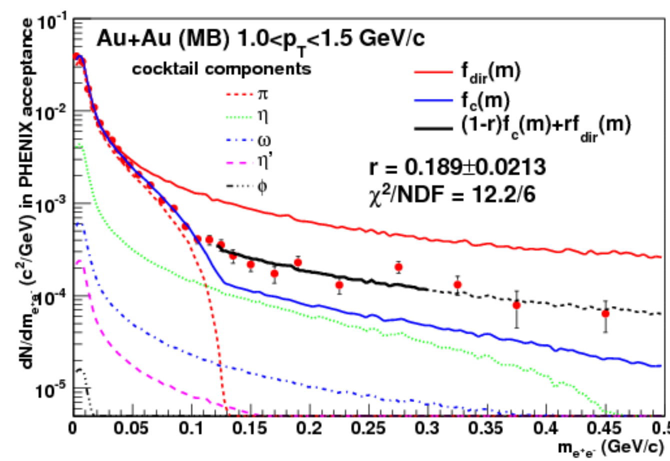




- Use e+ e- pairs
  - Good ID in PHENIX
  - $M_{ee} > M_{\pi}$

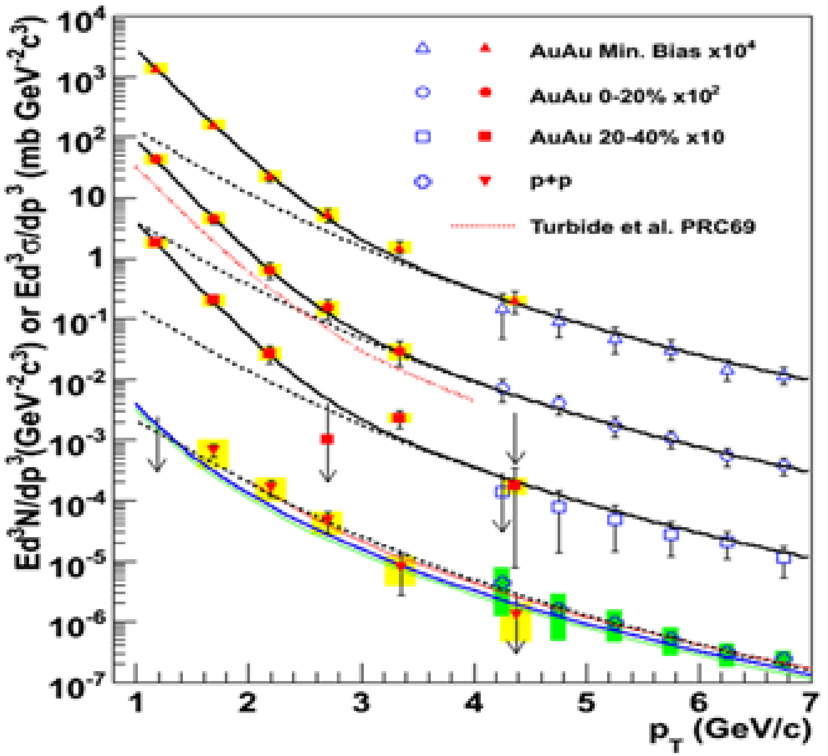
  Got rid of main background

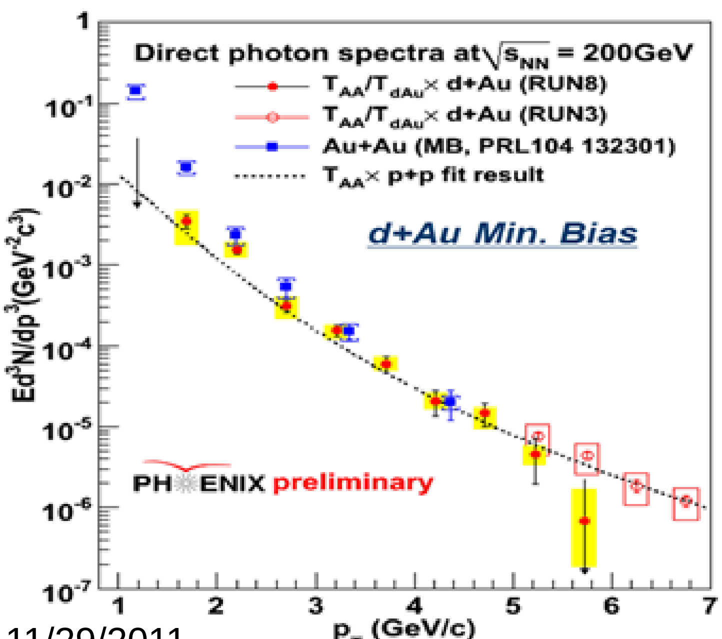
$$\frac{1}{N_\gamma}\frac{dN_{ee}}{dm_{ee}} = \frac{2\alpha}{3\pi}\sqrt{1-\frac{4m_e^2}{m_{ee}^2}}\left(1+\frac{2m_e^2}{m_{ee}^2}\right)\frac{1}{m_{ee}}\left|F(m_{ee}^2)\right|^2\left(1-\frac{m_{ee}^2}{M^2}\right)^3$$



Thermal photons

- Inclusive photon × $\gamma_{dir}/\gamma_{inc}$
- Fitted the spectra: p+p fit + exp
  - $T_{ave} = 221 \pm 19^{stat} \pm 19^{syst}$ MeV (MB)
- Initial properties from model calculations
  - T_{ini} = 300…600 MeV,
    ε_{init}~15 GeV/fm^3 , $p_{init} \geq 1.5$ GeV/fm^3





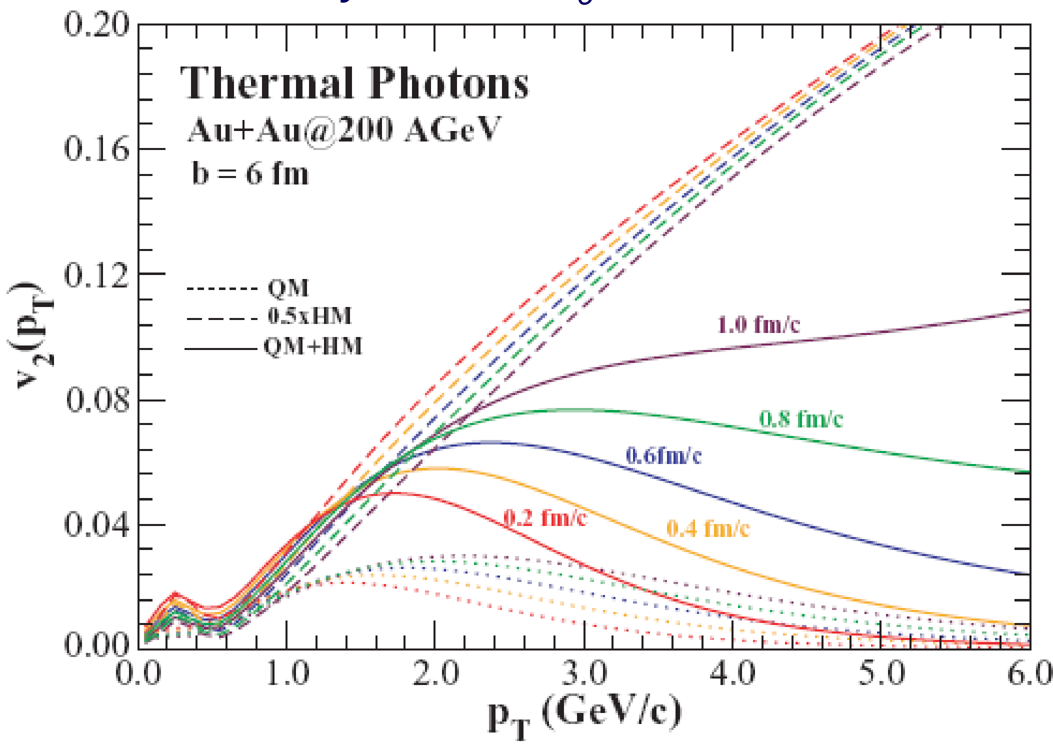
No excess in d+Au → not a nuclear effect

No hadronic matter can be this hot → sQGP

Direct photon flow (theory)

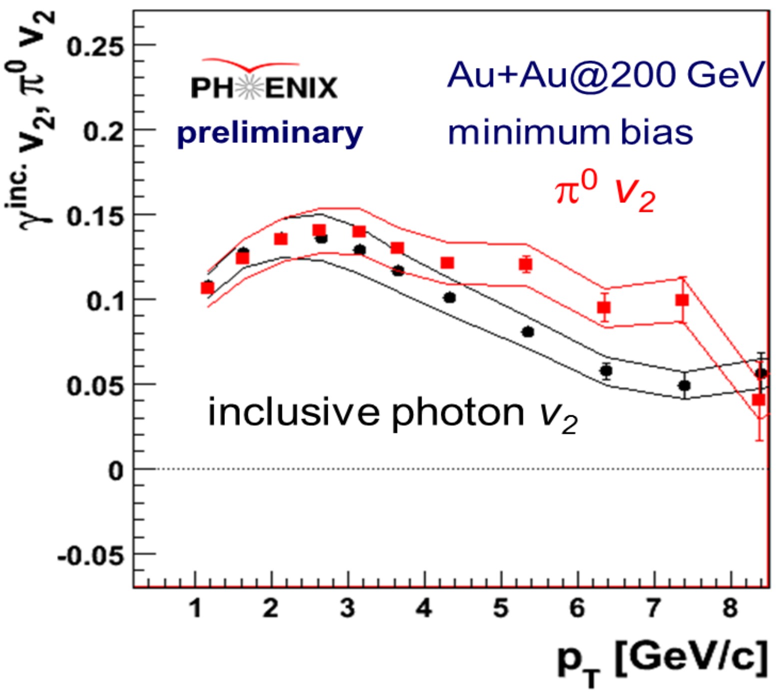
- Hydro expected v_2
  - Prompt photons: no flow
  - Early thermal photons: small flow
  - Later thermal photons: larger flow
- Further constrains T_{ini}

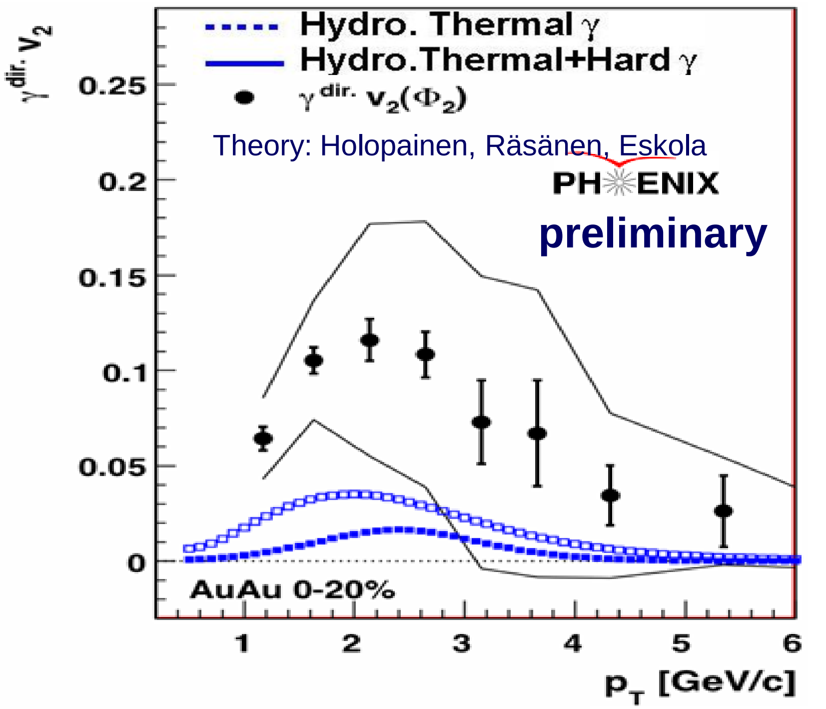
Hydro after τ_0



Chatterjee, Srivastava
PRC79, 021901 (2009)

Direct photon flow (1st time meas.)

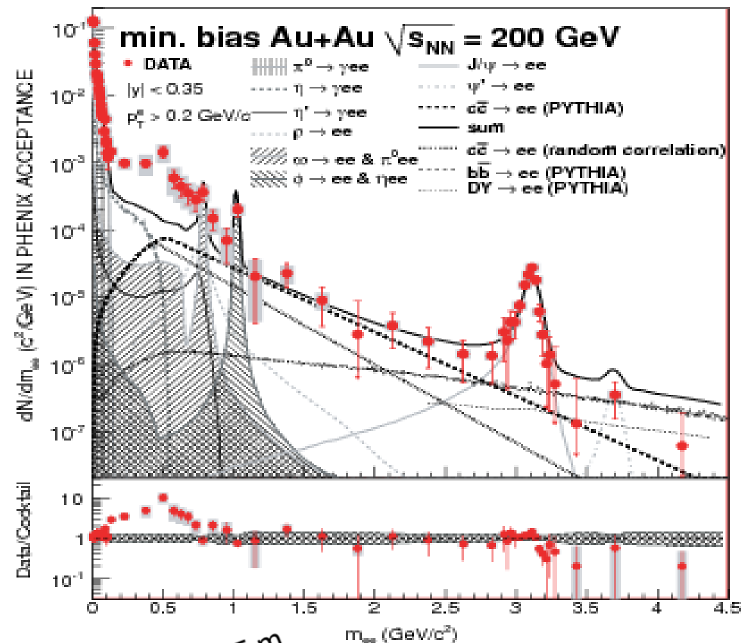


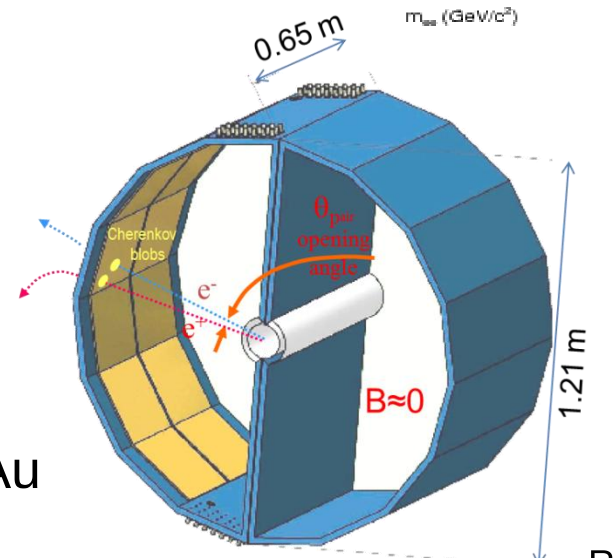


- inclusive photon v_2 similar to π^0 v_2
- Direct photon v_2 consistent with 0 at high p_T as expected
- But: comparable to π^0 v_2 at lower p_T
  - Most models underpredict direct photon v_2
  - Challenge to theory

Dielectron excess

- **Large excess** observed in Au+Au
  - A direct probe sensitive to in-medium properties of light mesons
  - Au+Au data **~5x** excepted from hadron cocktail
  - Concentrated at $m_{ee}<m_{\rho}$
  - No excess observed in p+p
- Room for improvement
  - Combinatorial background large
  - S/B in this mass region is 1/200
- **Hadron Blind Detector**
  - Windowless Cherenkov, B~0
  - Took data in 2009 p+p and 2010 Au+Au



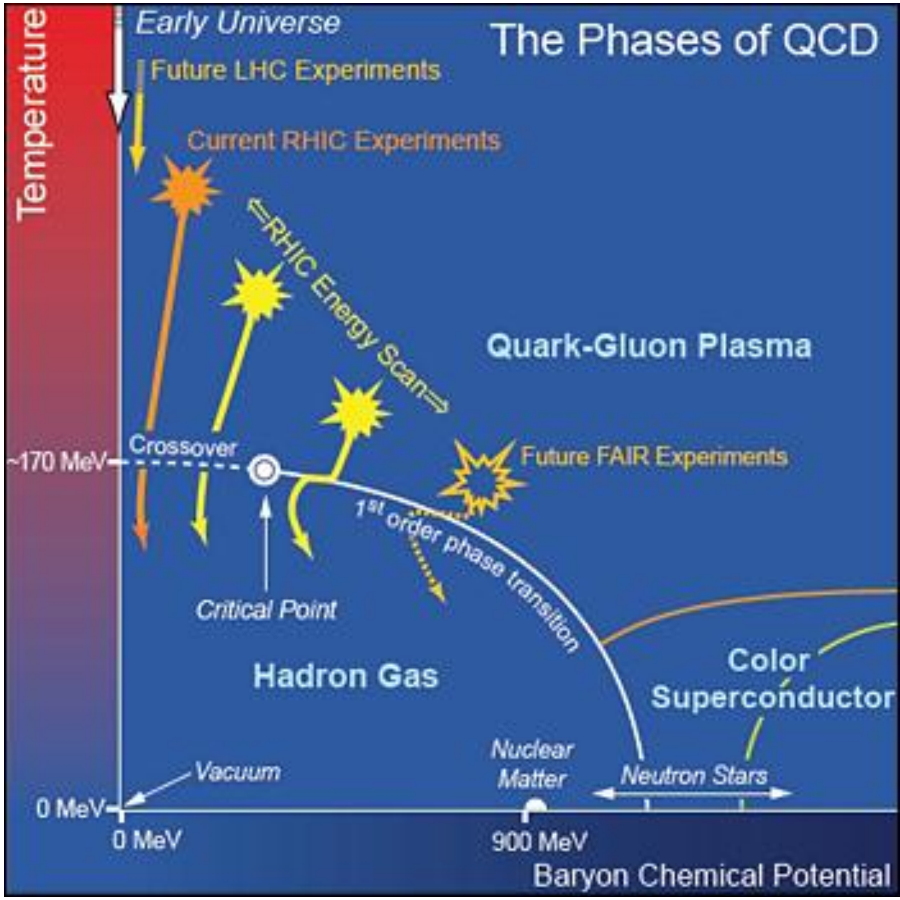


Understanding the phase transition

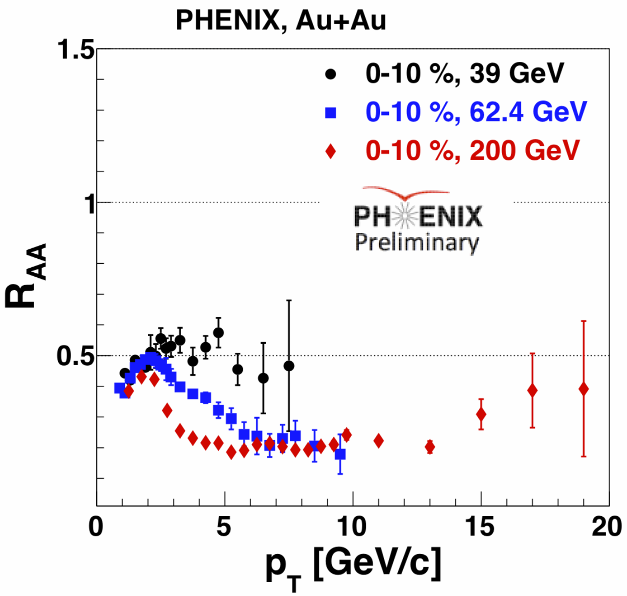
- How does matter transform?
  - Type of phase transition?
  - Critical point?
  - Relation of deconfinement and chiral transition?

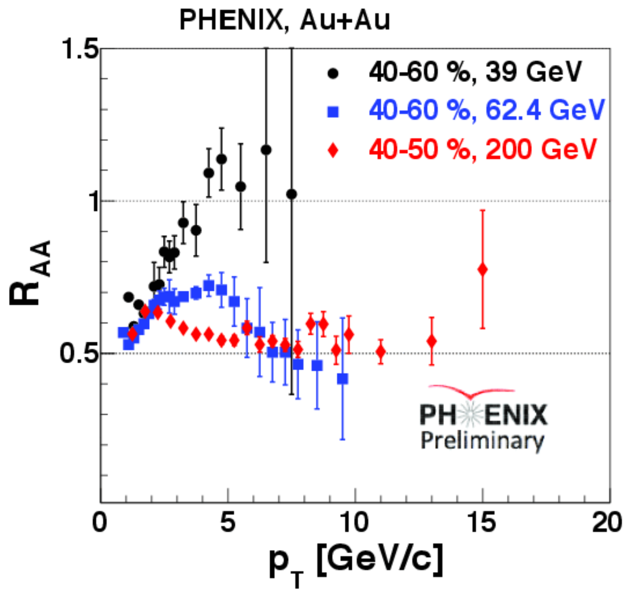
- **RHIC energy scan**
  - Probing different regions of the phase diagram
  - Au+Au from 7.7 to 200 GeV
  - Cu+Cu from 22 to 200 GeV
  - p+p from 62.4 to 500 GeV

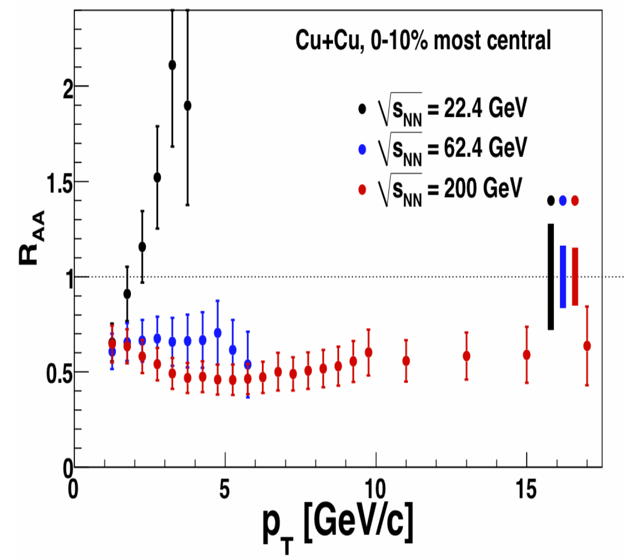
- Complementary to LHC data



π^0 R_{AA} system and $\sqrt{s}$ dependence

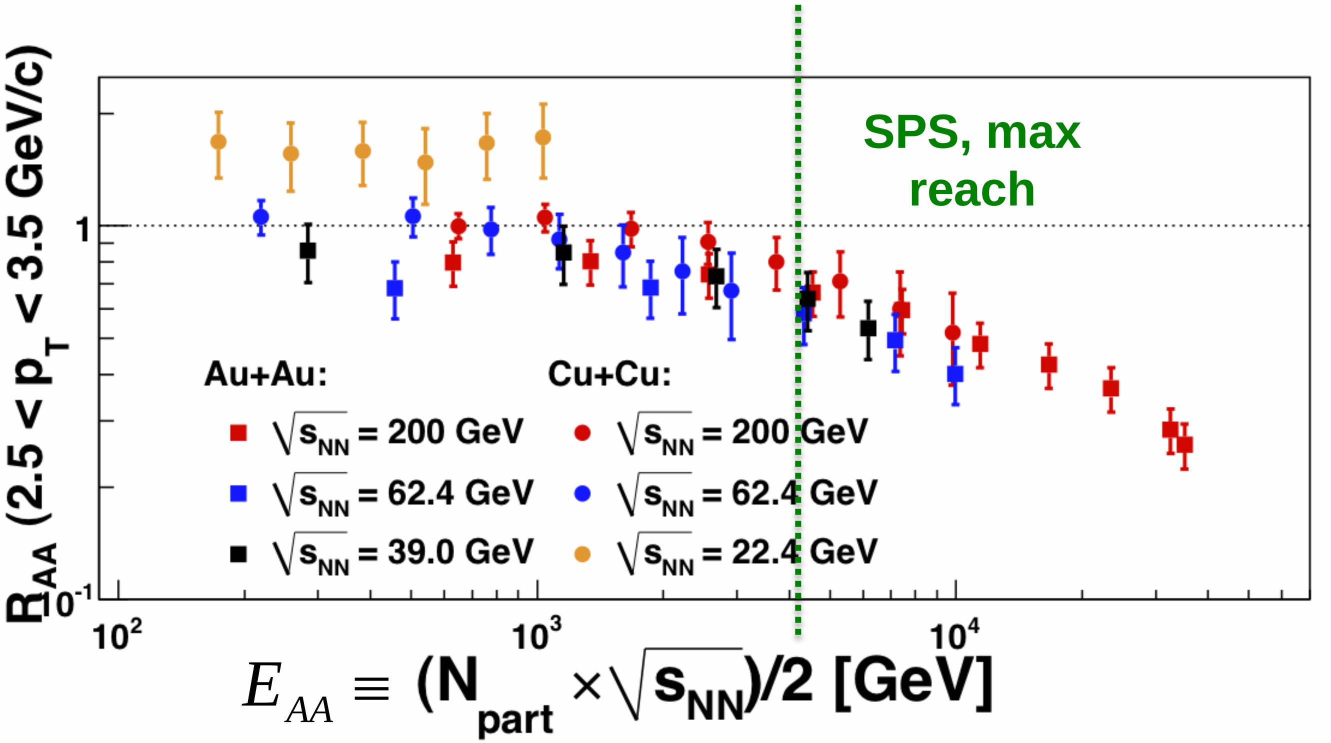






- **Significant suppression at** $\sqrt{s_{NN}}$ = 200 and **62.4 GeV Cu+Cu**
- **Still strong suppression** (factor of 2) in the **most central $\sqrt{s_{NN}}$ = 39 GeV Au+Au**
- R_{AA} from $\sqrt{s_{NN}}$ = **62 GeV Au+Au data is comparable with 200 GeV Au+Au** R_{AA} data for p_T 6 >GeV/c
- Peripheral $\sqrt{s_{NN}}$ = 62 and 200 GeV data show suppression
- **No suppression in peripheral $\sqrt{s_{NN}}$ = 39 GeV**
- **Moderate enhancement at central $\sqrt{s_{NN}}$ = 22.4 GeV Cu+Cu**

π^0 R_{AA} vs. total system energy



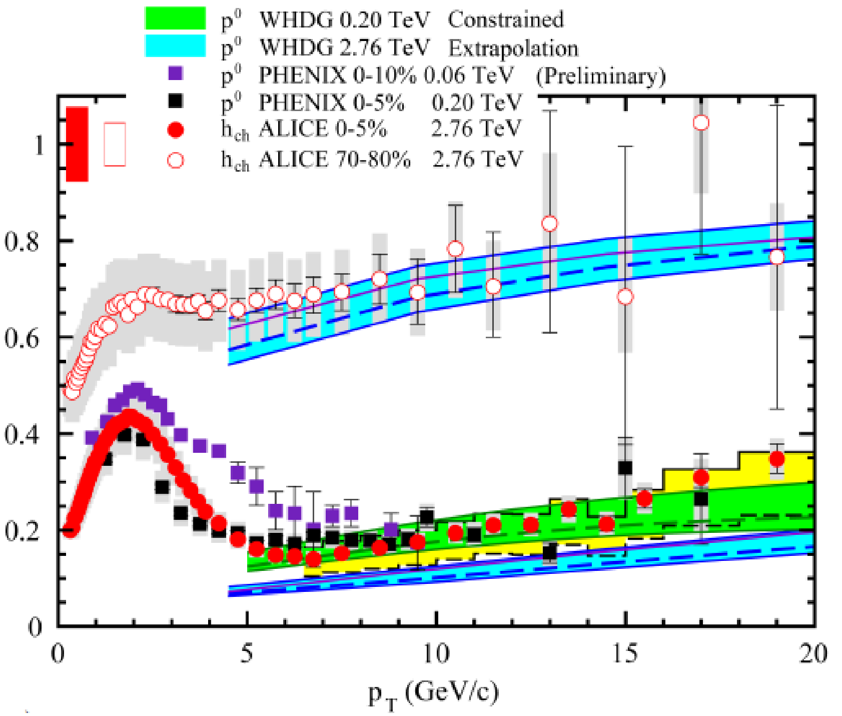
System size:

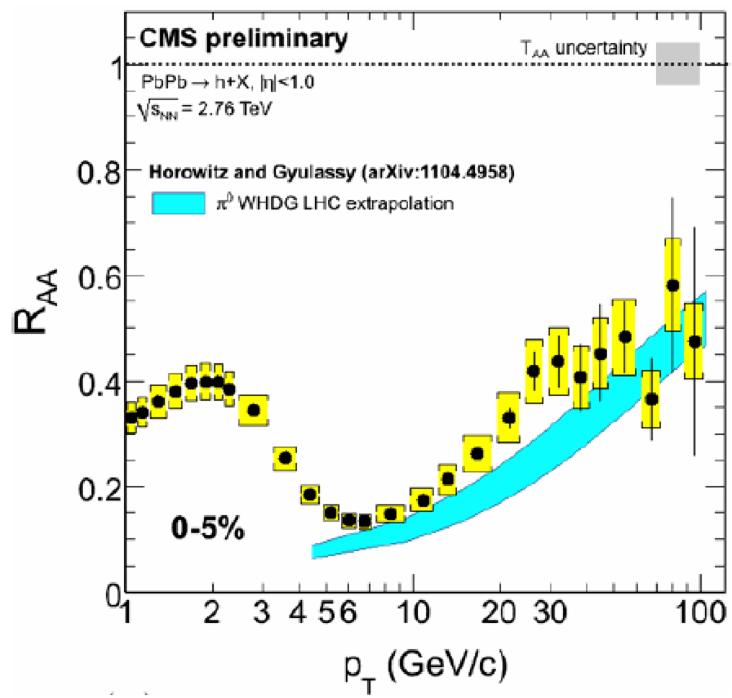
- **Circles: Cu+Cu**
- **Squares: Au+Au**

SPS, max reach: 2 × 208(Pb) × 17.3 GeV ($\sqrt{s_{NN}}$)/2 = 3598.4 GeV

- All the R_{AA} values show the same trend.
- No exact scaling for all p_T ranges

R_{AA} – RHIC vs. LHC

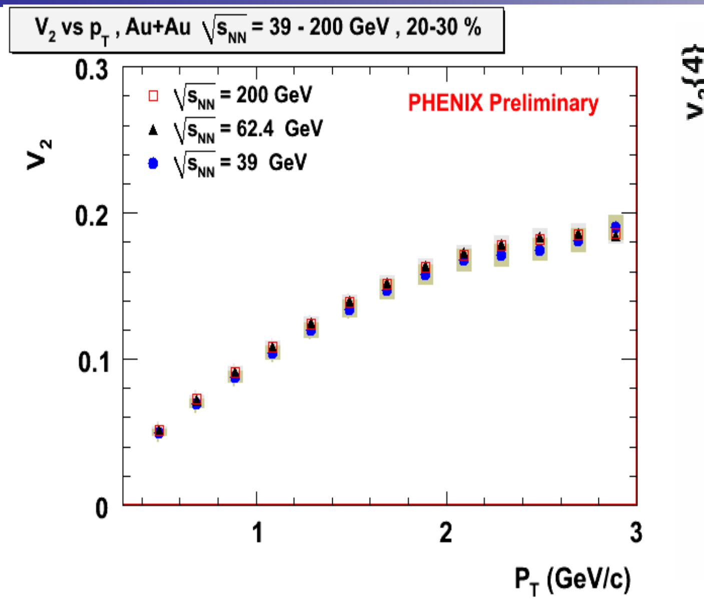


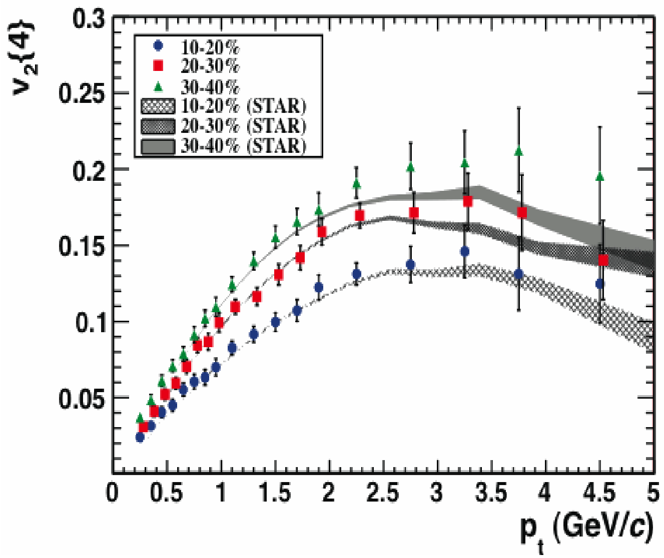


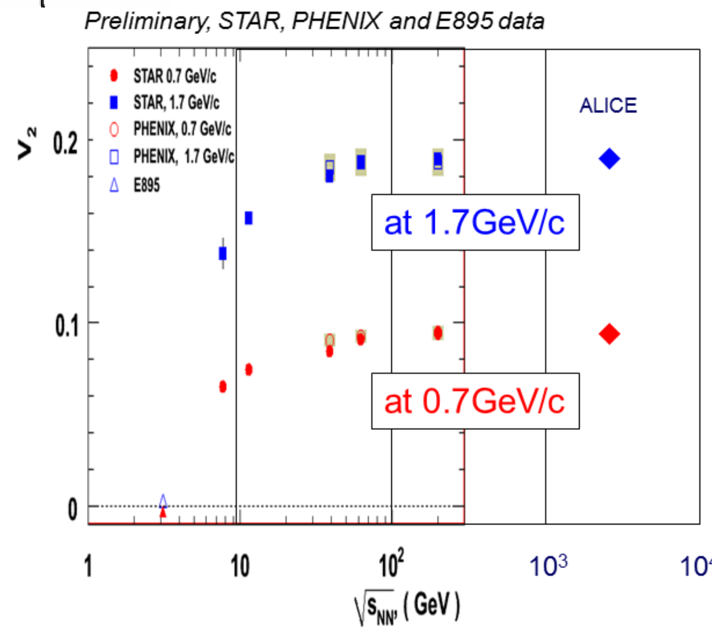
- Suppression surprisingly similar!

- RHIC: R_{AA} consistent with constant above p_T~5 GeV
- LHC: Definite rising trend

Same perfect fluid at RHIC and LHC



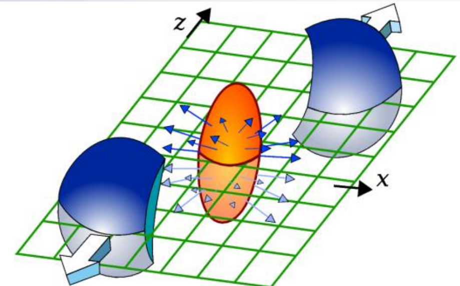




- Similar hydro properties

  v_2 at given p_T saturates around or below 39 GeV
- Almost perfect fluidity from ~39 GeV to 2.76 TeV

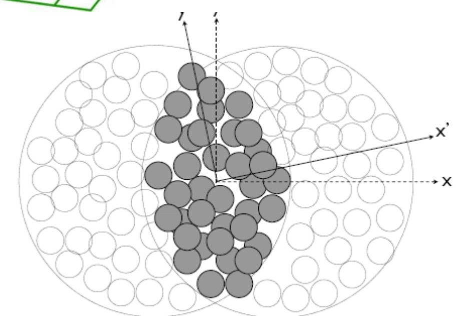
Event-by-event fluctuations and v_3



- Approach before 2010:

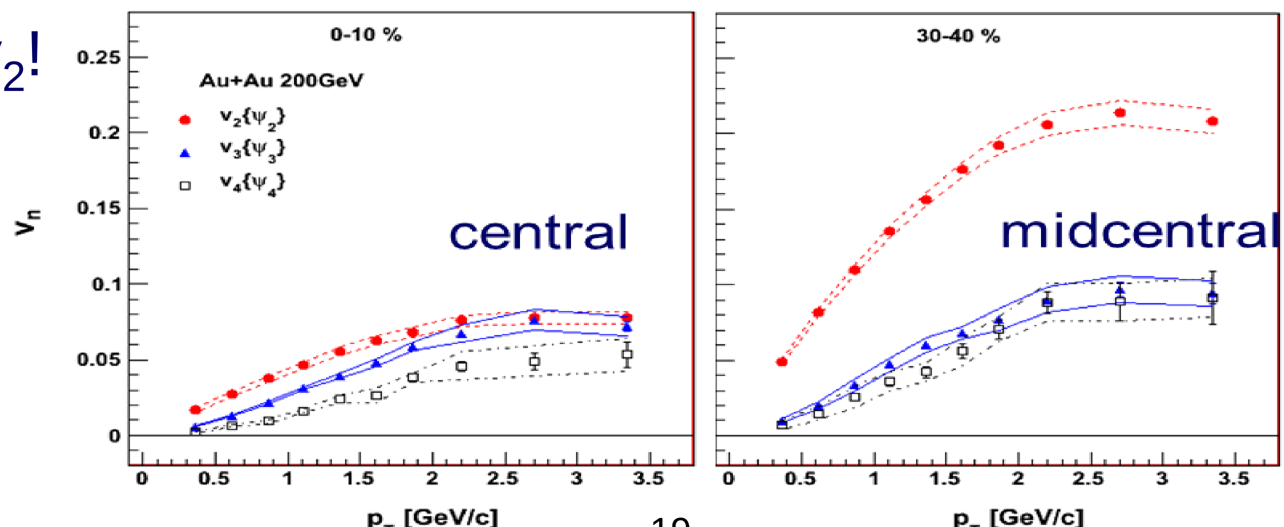
$$\frac{dN^{\text{pairs}}}{d\Delta\varphi} \propto \left(1 + \sum_{n=1} 2 v_n^a v_n^b \cos(n\Delta\varphi)\right)$$

  - Symmetry: no odd components $(\varphi \rightarrow \varphi + \pi)$



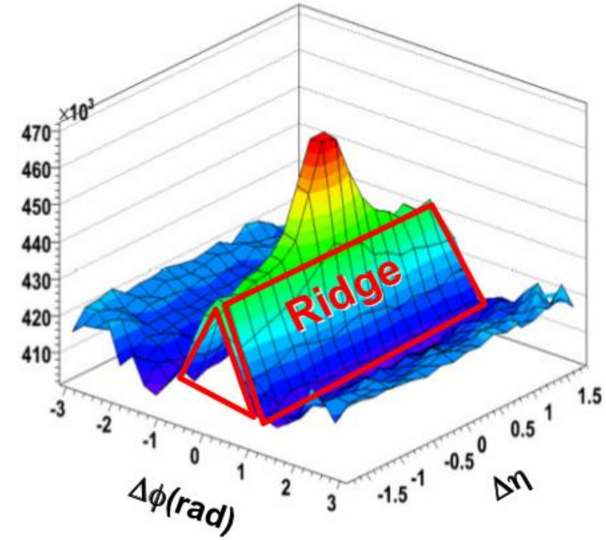
- B. Alver and G. Roland (May 2010)
  - Events are different – fluctuations
  - Triangularity → v_3

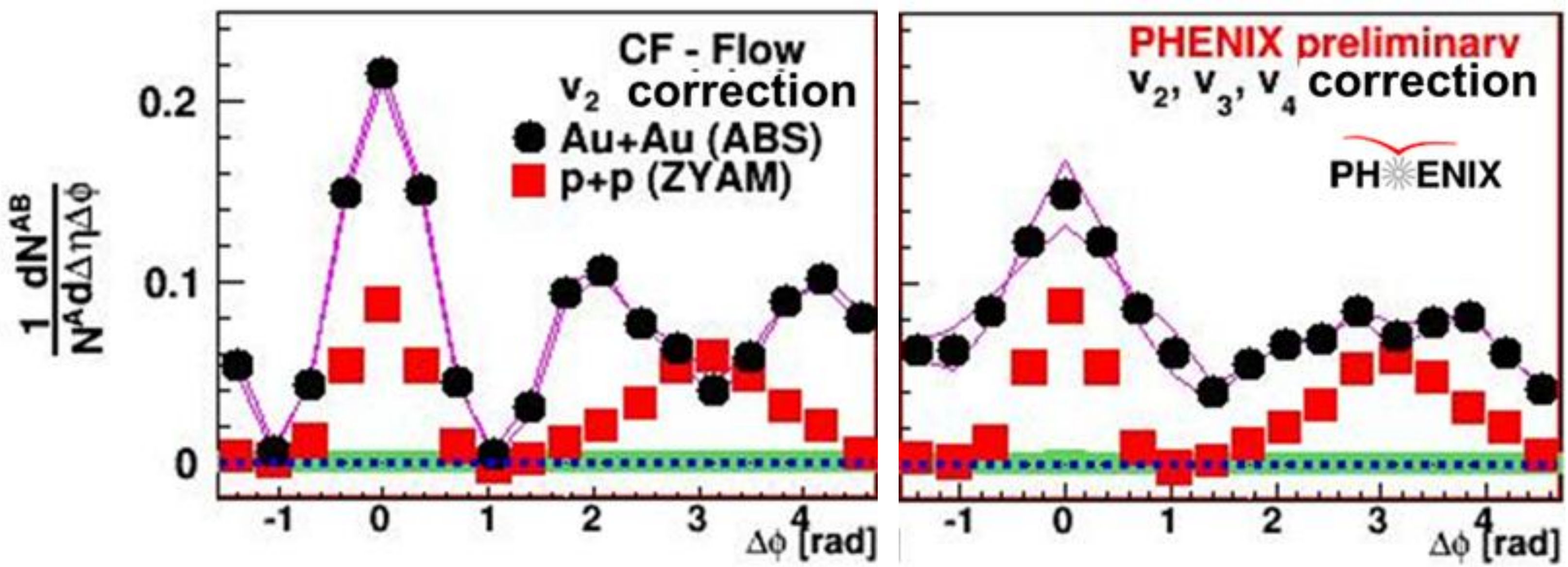
- $v_3 \sim v_2$!



v_3 explains Mach cone and ridge

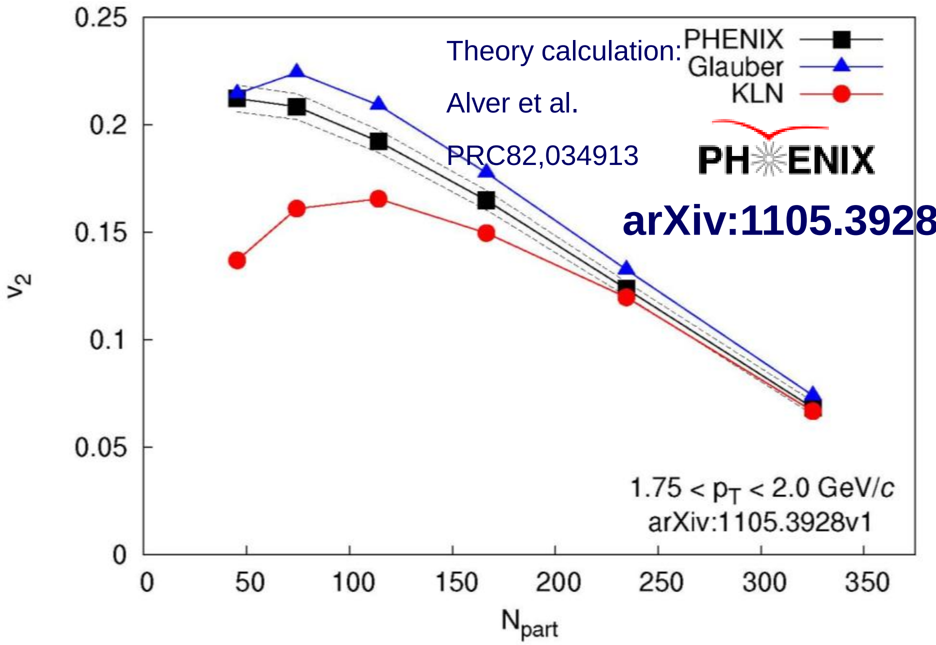
- High pT hadron correlations
- Ridge: Long-range near side η correlation
  - Initial fluctuation is common!
- Mach Cone: away side double peak in central collisions



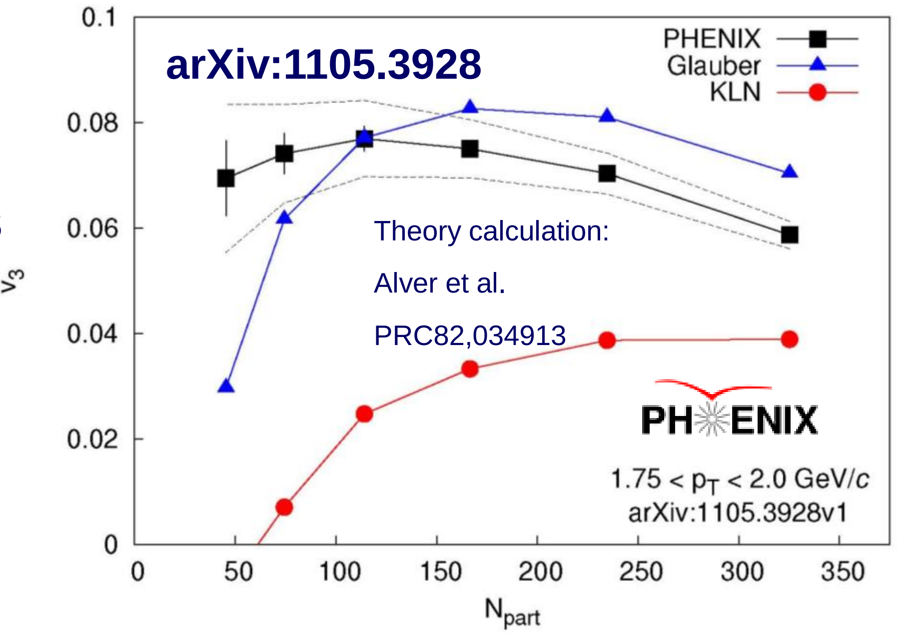


v_3 disentangles initial state and η/s

v_2 described by Glauber and CGC

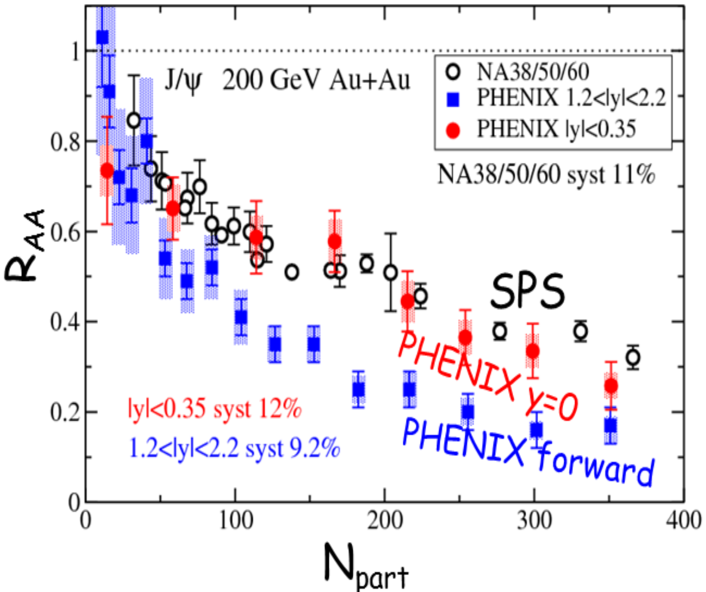


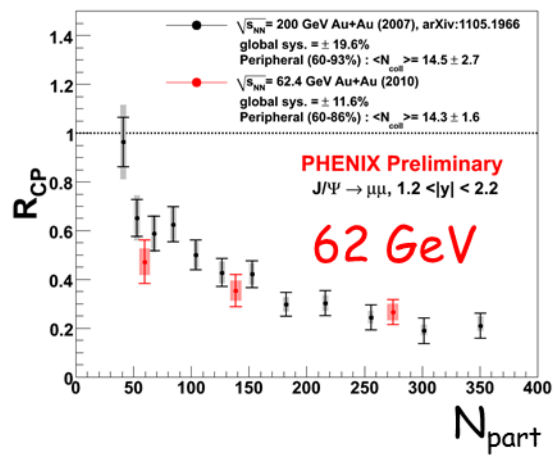
v_3 described only by Glauber

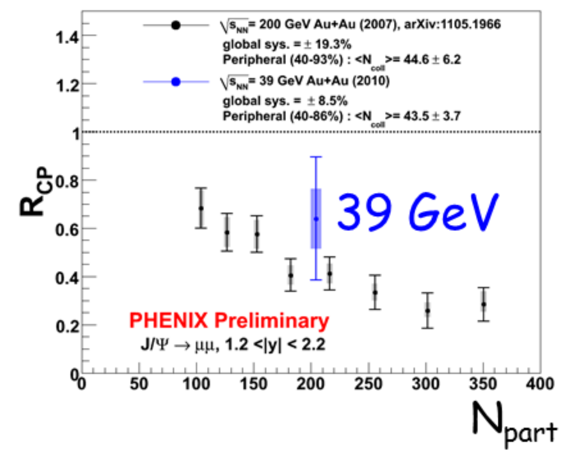


Glauber initial state ($\eta/s = 1/4\pi$) favored and
CGC initial state ($\eta/s = 2/4\pi$) disfavored by v3

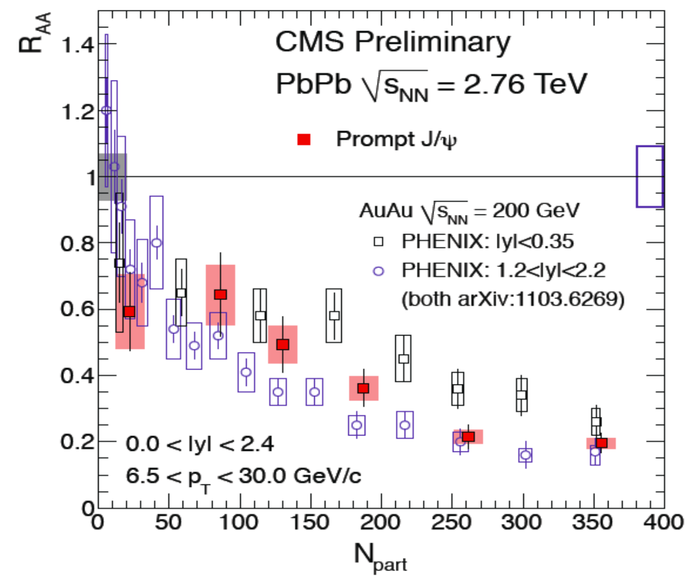
The J/ψ puzzle





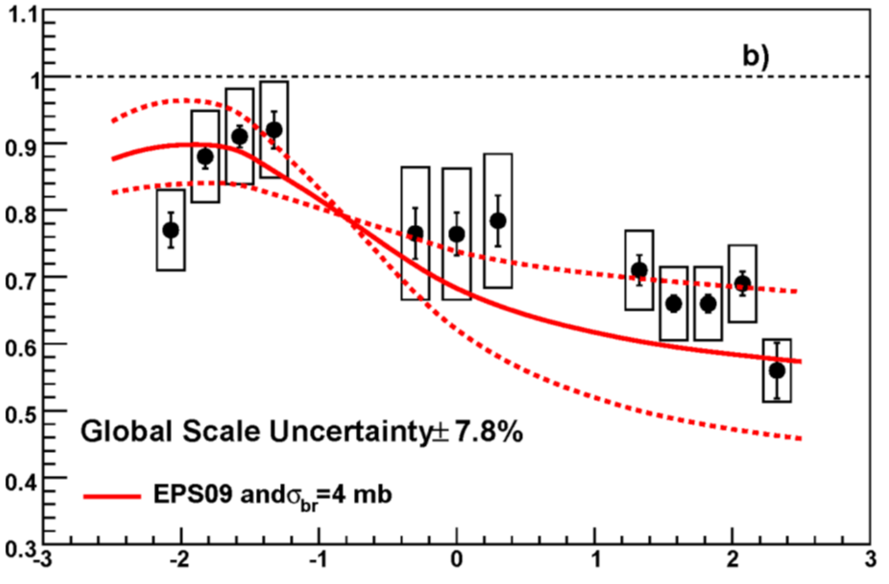


- General picture at mid-rapidity: J/ψ suppressed to approx. the same extent at
  - SPS (17.2 GeV)
  - RHIC (200,62,39 GeV)
  - LHC (2.76 TeV).

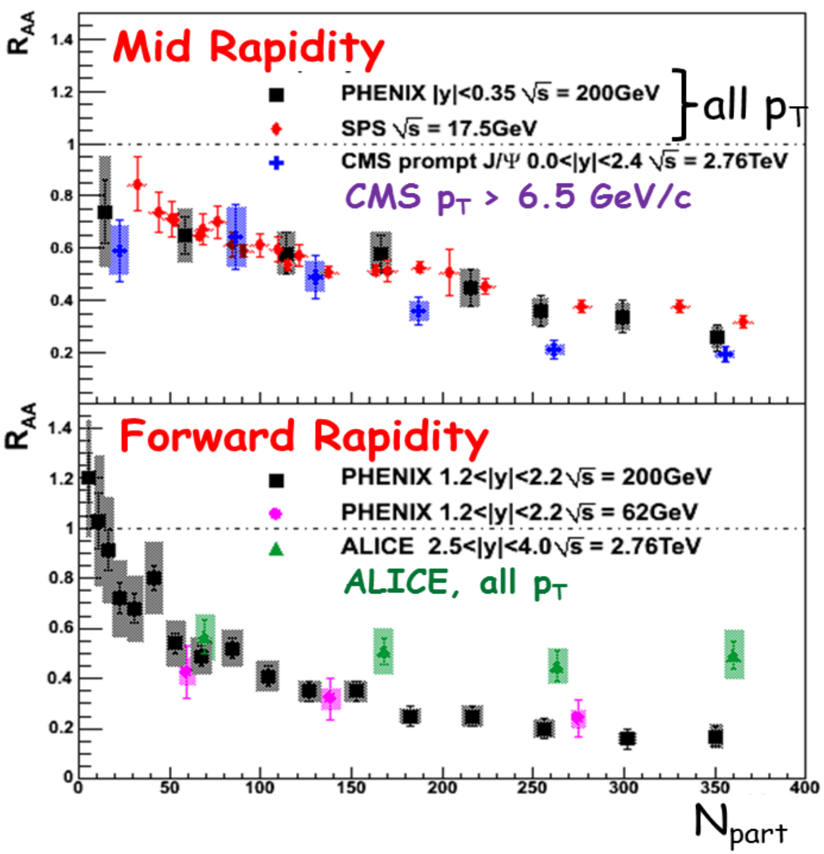


- STAR: J/ψ does not flow (much)

The J/ψ puzzle



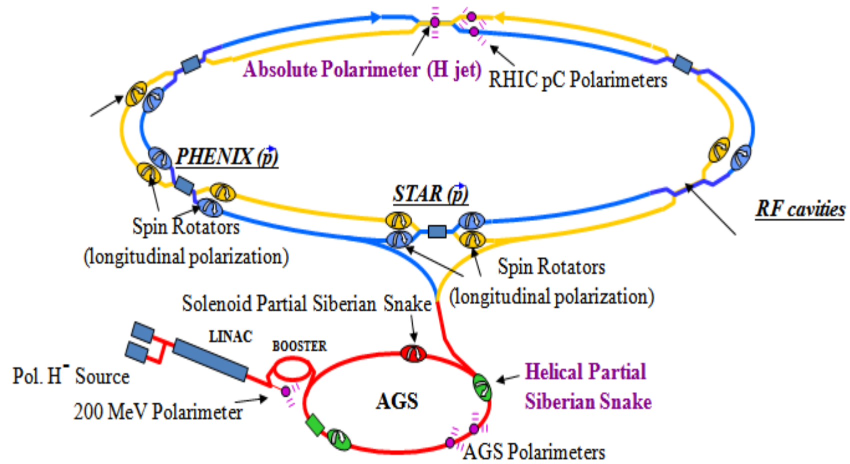
- Less suppression in central than forward Au+Au



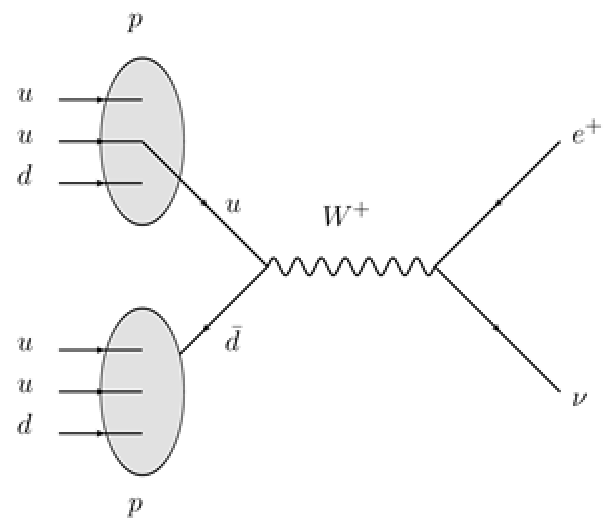
- Suppression in forward d+Au
  - CNM "baseline"
  - Several contributors, hard to disentangle
  - Challenge for models

RHIC spin

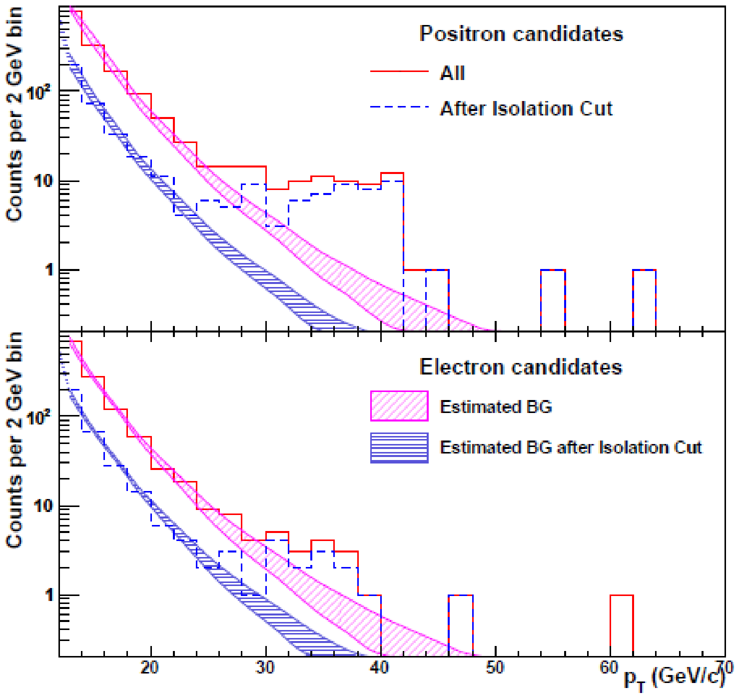
- Polarized pp collisions
  - Varied spin orientations
  - First W observations 2009
  - Improved capabilities in 2011



- Purpose
  - Parton contribution to proton spin?
  - $u_L \bar{d}_R \rightarrow W^+, \;\; d_L \bar{u}_R \rightarrow W^-,$
  - W^+/W^- ratio: access to polarized PDF's

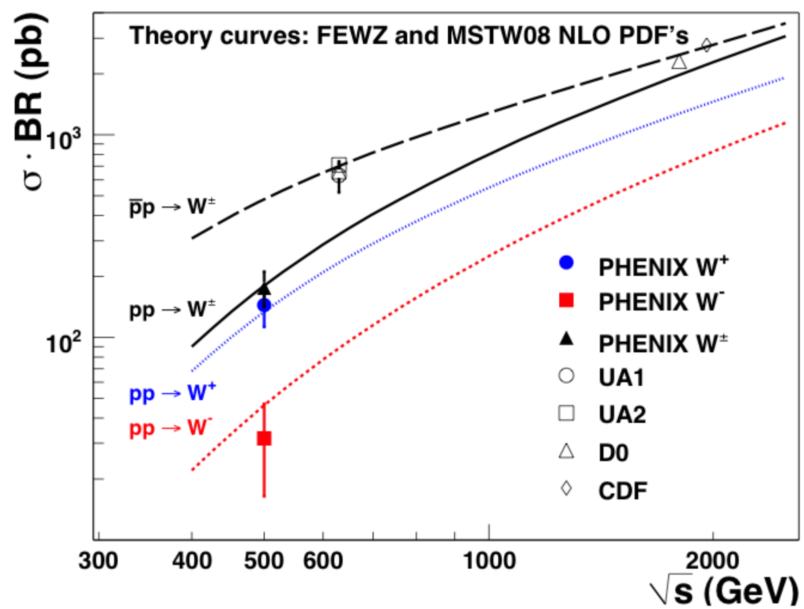


$W^{+/-}$ results

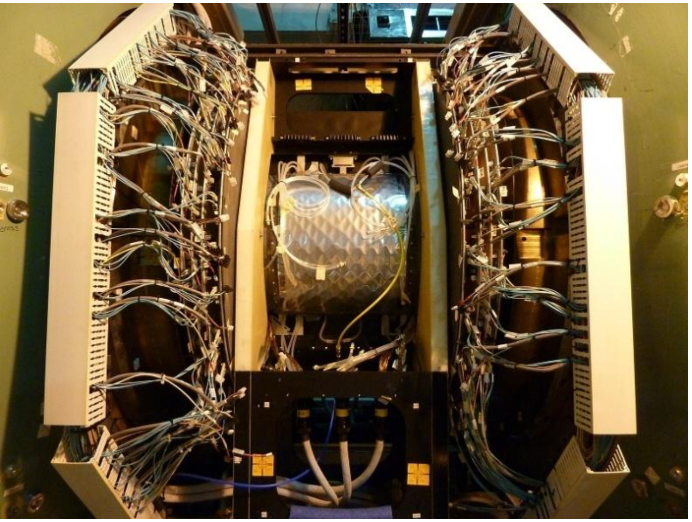


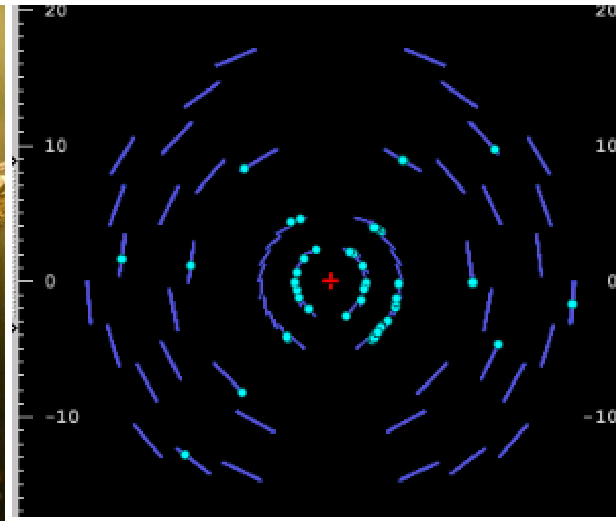
- Asymmetry
  - 42 “+” candidates
  - 13 “-” candidates

- X-section vs. calculations

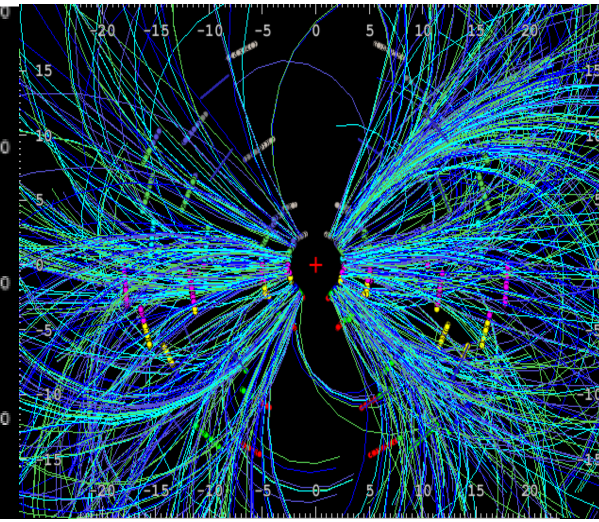


Underway: Silicon Vertex Detector





p+p@500 GeV, 2011

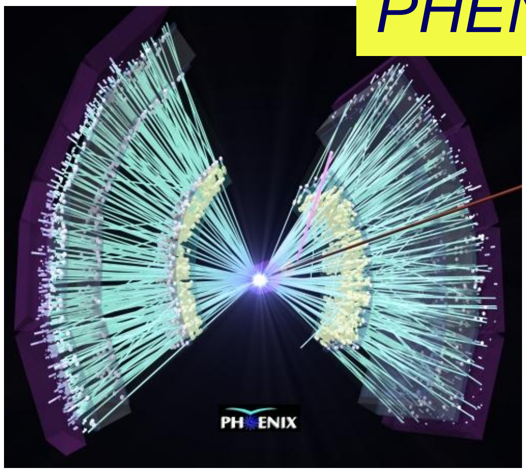


Au+Au@200 GeV, 2011

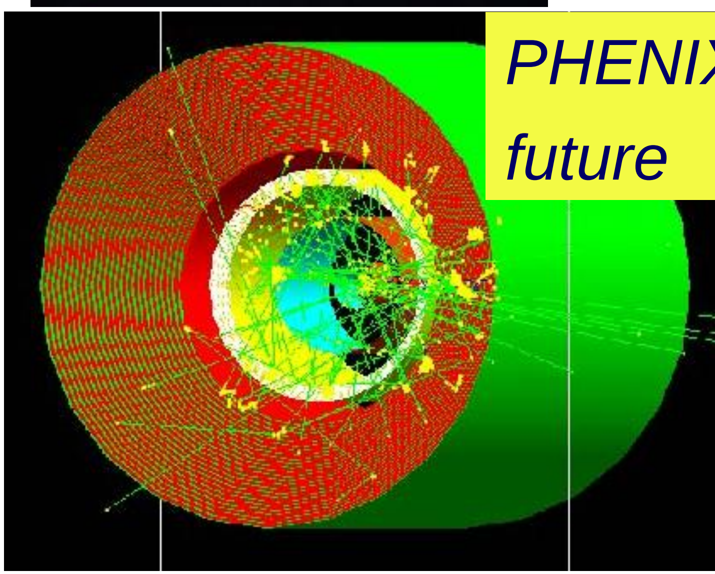
- Status
  - VTX successfully commissioned in 2011 *p+p* run
  - VTX taking data in Au+Au
- Physics
  - R_{AA} of *c*, *b* separately
  - v_2 of *c*, *b* separately
  - Jet tomography (di-hadron, γ-*h*, *c*-*h*, *c*-*c*)

The next decade

PHENIX now



PHENIX future



- Midterm physics plan

  Installation of current upgrades- heavy flavor, forward photons

- sPHENIX physics plan

  Major detector configuration change with exciting prospects
  A new era in jet physics at RHIC!

- SuperQCD Era
  - RHIC + eRHIC with PHENIX EIC capabilities

Summary

Covered (to some extent):

- Jet suppression, its onset
- Flow (v2, v3) , its onset
- Direct probes: photons, electrons
- J/psi suppression, cold nuclear matter effects
- Spin: parity violation, W
- Some history and plans

Only a fraction of topics

Thank you!

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